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Collaborative Task Performance for Learning Using a Virtual Environment

Abstract

This paper describes a study on the sense of presence and task performance in a virtual environment as affected by copresence (one subject working alone versus two subjects working as partners), level of control (control of movement and control of navigation through the virtual environment), and head tracking. Twenty subjects navigated through six versions of a virtual environment and were asked to identify changes in locations of objects within the environment. After each trial, subjects completed a questionnaire designed to assess their level of presence within the virtual environment. Results indicated that collaboration did not increase the sense of presence in the virtual environment, but did improve the quality of the experience in the virtual environment. Level of control did not affect the sense of presence, but subjects did prefer to control both movement and navigation. Head tracking did not affect the sense of presence, but did contribute to the spatial realism of the virtual environment. Task performance was affected by the presence of another individual, by head tracking, and by level of control, with subjects performing significantly more poorly when they were both alone and without control and head tracking. In addition, a factor analysis indicated that questions designed to assess the subjects' experience in the virtual environment could be grouped into three factors: (1) presence in the virtual environment, (2) quality of the virtual environment, and (3) task difficulty.

1 Introduction: Virtual Environments and Education

Along with the continuing development of virtual environment (VE) systems, there is a small but growing body of empirical research on the use of VEs in education, training, and learning. Although this research is still in a fairly early stage, there is growing evidence that VEs can be effective tools in education, training, and learning. A number of studies have identified several aspects of the use of virtual environments that seem to promote effective learning. One aspect is the ability to use VE display technology to allow students to experience realistic simulations of subject matter in a variety of educational domains, stimulating their interest and increasing their understanding of the material. For example, subjects such as history or geography contain material that could be modeled and displayed using 3-D display technology, such as a reconstruction of an archeological site (Sanders, 1997). In addition, more-abstract concepts such as forces studied in statics and dynamics classes or in physics and chemistry could be modeled and presented to students. For example, Salzman, Dede, Loftin, and Sprague (1997), Dede, Salzman, and Loftin (1994), and

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Brelsford (1993) indicate that presenting abstract concepts in physics using 3-D display technology can assist students in forming more-appropriate mental models of the material. Similarly, Byrne (1996) found that using virtual environments to present concepts in chemistry can also help students better learn the material. These simulations can easily represent concepts (such as gravity, velocity, force, momentum, or electrical charge) that can be difficult for students to grasp via conventional pedagogical presentations such as lectures or regular physics or chemistry labs.

This use of VE technology may represent a significant improvement in the quality of the learning experience and may be a significant enhancement to learning. However, a number of questions are raised by the introduction of VE technology into the classroom. For example, what specific VE display technologies will be needed to support specific aspects of learning? Will VE technology affect collaboration among students? Will VE technology require teachers to adapt new teaching methods? How should performance in an educational setting be evaluated to measure the impact of VE technology in the classroom? The answer to these questions will involve close collaboration between those traditionally involved in secondary and higher education as well as those involved in the design and evaluation of VE systems. Further, while many of the traditional measurement and evaluation techniques used in education will be transferable to learning scenarios using VE technology, additional techniques will also have to be developed.

This paper reports the results of a study that examined a number of issues that may affect education and task performance using VE technology. Specifically, we were interested in three factors within VEs that we believed would have an effect on the use of VEs in learning: (1) determining whether task performance and presence were affected by collaboration, (2) determining whether task performance and presence were affected by control of movement and navigation through the virtual environment, and (3) determining whether presence and performance within the VE were affected by the use of head tracking.

2 Interaction in VEs: Presence, Collaboration, Control, Performance

One factor that may be of particular concern for education using virtual environments is the students' sense of presence in the VE (Psotka, 1995; Winn, 1995, 1996, 1997). The sense of presence is the experience of ''being there'' in a VE (Barfield, Zeltzer, Sheridan, & Slater, 1995; Hendrix & Barfield, 1996a, 1996b; Bystrom & Barfield, 1996). Depending on the purpose of the VE, its users' sense of presence may have significant effects on the usefulness of that environment (Mowafy, Russo, & Miller, 1993; Barfield et al., 1995). For example, in a VE used as a flight simulator, it may be beneficial for the user to have a high level of presence in order to support transfer of training from the simulator to the real-world aircraft, while in VEs used for group decision making, a high level of presence may result in students feeling as if they were collaborating together in the same place (Suzuki, Sugawara, Watanabe, & Nagashima, 1993, p. 78). In fact, past research (Winn, 1995) found that high levels of presence were associated with learning. In the Winn study, the virtual environments were designed and partially built by the students themselves, and knowledge of content was tested after the students experienced the VEs.

A second factor that may play an important role in the usefulness of virtual environments in education is the ability of students to collaborate while within the virtual environment. Researchers have argued that collaboration in virtual environments is likely to promote learning by enabling students to work together to understand problems and construct accurate mental models of knowledge domains (Winn, 1997; Dede, 1995; Rose, 1995). Based on current technology, there are two main ways by which multiple participants can share the same VE: distributed virtual environments and what we term ''copresent'' virtual environments. In distributed VEs, the multiple participants are at different physical locations with respect to each other. Each user views the same virtual environment, but can have a different view of the VE based on individual eyepoint location or head tracking. In contrast to distributed VEs, the participants in copresent VEs share not only the same representation of a three-dimensional database, but also share the same visual display and physical space within an environment. They are physically present next to each other in the same room, looking at the same display. Given the current costs and technical problems associated with designing and implementing distributed VEs, schools may likely develop VEs that allow students to access the same VE simulation in the same place at the same time.

The issue of multiuser participation within VEs is a particularly relevant topic for research in education and training, given the proliferation of distributed VE systems and the importance of VEs to support group decision making. One issue of special concern in multiuser VEs is the affordances for communication provided by the VE system. Differences in communication affordances (resulting from particular technologies to present information) may affect the nature of interaction between participants. Yoshida and Kakuta (1994) note the value of face-to-face interaction in communication, in contrast to computer-mediated interaction. They found that face-to-face communication provides for swift, effective feedback from other participants, and that discussion tends to be of a higher fidelity and more on-topic than discussions conducted via technological media such as virtual avatars. A similar trend is reported by Hirose, Taniguchi, Nakagaki, and Nihei (1994) in an investigation of virtual playgrounds and communication systems for hospitalized children; they found that providing a high-quality means of communication between participants was important in developing an engaging experience. These studies suggest that copresent virtual environments may be particularly useful for certain education applications by affording high-quality, face-to-face interaction. Based on these studies, it also seems likely that a high level of presence may be beneficial for distributed and copresent VE applications, as a high level of presence would encourage the students to believe that they are sharing the same virtual space. The studies by Curtis and Nichols (1994) and Hirose et al. (1994) also suggest that the interpersonal interaction in distributed environments may in turn yield a higher sense of presence by providing a more engaging experience. Therefore, one goal of this study was to examine the effects of copresent collaboration on the sense of presence and on task performance.

Another factor in the use of copresent VE systems is the degree of control the participants have over their interactions with the VE. The copresence of participants in VE systems may affect the participants' interaction with the VE, and thus affect their sense of presence in the VE. Robinett (1994) notes that, in copresent systems, only the driver, not the observers, typically interacts directly with the environment. Hence, there may be differences in the participants' sense of presence and quality of experience in the VE depending on the level of control each respective participant has over the interactions with the environment. For example, Mowafy et al. (1993) report that participants can experience different levels of psychological immersion in tasks that involve interacting with VEs; these different levels of immersion help determine the sense of presence in the VE. So, if participants must interact with a VE while performing a task in the real world, for example, the real-world task may conflict with the immersion in the VE, thus reducing the participants' sense of presence. Loomis (1993) provides support for this reasoning, noting that the participants' experience will probably be one of being in one location but in touch with a simulated environment (p. 54), thus experiencing distal attribution but not presence.

A final issue related to copresent virtual environments, one that is arguably fundamental to all research in the field, is that of task performance in the virtual environment (Barfield et al., 1995; Slater, Linakis, Usoh, & Kooper, 1996). In many cases, the purpose of virtual reality systems is to enable users to perform tasks that would otherwise be more difficult or impossible to carry out; these tasks can range from scientific visualization to training. Because of the importance of task performance, it is of interest to designers of virtual reality systems to investigate elements of users' experience in VEs that affect their ability to perform tasks in VEs. For example, Slater et al. (1996) posit that a high level of presence in a VE used for training will facilitate transfer-of-training from the VE to the real world, as highly present participants would behave in the VE as they would behave in the real world, although presence may not affect task performance within the VE itself. Slater et al. (1996) further posit that sensory immersion will yield improved task performance for tasks that require users to process and comprehend complex spatial information, as immersive displays typically provide richer spatial information than nonimmersive displays. Because realistic spatial information also enhances the sense of presence in the VE, high levels of presence are likely to be associated with improved task performance, although presence itself may not contribute directly to performance. Slater et al. (1996) found that an immersive stereoscopic display yielded better task performance on a spatial task (reproducing the positions of chess pieces on a three-dimensional chess board) than a monoscopic display using a television monitor. A more realistic-appearing environment also yielded better task performance.

3 Methodology

3.1 Experimental Design and Task

This study addressed issues of communication and interaction in a virtual environment. It investigated the effects of copresence (one participant working alone versus two participants working together), level of control (control of movement and navigation; control of movement but not navigation; control of navigation but not movement; control of neither movement nor navigation), and head tracking (head tracking versus no head tracking) on the sense of presence and task performance in a virtual environment.

The task in the study was to navigate through a virtual environment, locate objects within it, and mark the locations of those objects on printed diagrams. This task was chosen because it was a generic task whose elements were directly applicable to the use of virtual environments in education and training (and, in fact, to the more-general use of VEs). First, it required the subjects to do a large amount of navigation through the virtual environment, thereby increasing their exposure to the environment. It also required the subjects to act both within the virtual environment (as they located objects) and outside the virtual environment (as they marked the locations of the objects on the printed diagrams). This simulated the real-world use of nonimmersive collaborative VEs, as users of those environments would also need to perform actions both inside and outside the VE. The task was also designed to be appropriate for collaboration, as two heads (might be) better than one when locating and evaluating the positions of objects in the virtual environment; this is similar to the use of VEs for architectural modeling and walkthroughs. Last, it focused on psychomotor performance, encompassing both motor (navigation) and cognitive components (search and decision making), rather than on a purely cognitive task (as a VE used to present a virtual chessboard might be, for example), because it was decided that both aspects of performance were important for virtual environments in education or training.

The virtual environments that the subjects experienced were six variants of a virtual room and its furnishings, including objects such as tables, chairs, a desk, a bookshelf, a telephone, a notepad, and so forth. Each variant was created by relocating certain objects to form a different decoration of the room. No objects were ever removed, and there was always the same number of objects in the environment; this ensured the same level of complexity and the same update rate in each environment. Figure 1 shows one variant of the virtual room.

Each subject experienced a total of six treatments, two treatments working alone and four treatments working with a partner. At the beginning of each treatment, the subjects were given a printout of a top view of a prototype version of the virtual room. (This diagram was identical in each trial.) At the beginning of the first trial, the subjects also received printouts of two screen shots taken from eye level, facing in opposite directions in the prototype room; these diagrams were to give the subjects a better idea of the spatial relationships between the objects in the room than was possible with the top-view diagram. In each trial, the subject(s) started outside the room, navigated through the room, identified which objects had been moved from their positions as indicated on the diagram, and marked the top-view diagram to

Figure 1. *Representation of the virtual world.*

show the changes in location. For example, if a chair had been moved, they might circle the chair on the diagram and draw an arrow to its new location in the virtual environment. The size of the room and the placement of the objects required the subjects to navigate through the room in order to view all of the objects. The following two treatment conditions represent performance for a single user, and these were included to provide a baseline performance for the copresent conditions.

- Alone / Active: The subject was head tracked. The subject was free to choose (via the mouse) where to move within the environment.
- Alone / Passive: The subject was not head tracked. The subject had no control over movement in the virtual environment, but instead was taken on a preset ‘‘guided tour’’ along a predetermined path through the environment. This path was a circuit of the inside of the room; all of the objects were visible from this path.

In the shared treatments described below, both subjects participated in the task, working as partners. Both subjects had diagrams to mark changes in locations of objects. The subjects could speak together freely; for example, they could discuss where to go within the room, what objects to look for, or could point out objects that had been moved. The treatments differed in their level of control over the mouse, over where to move within the virtual environment, and in the presence or absence of head tracking. There was no condition in which the subjects could negotiate for control; this was due to a decision to always pair head tracking with control of the mouse, and head tracking needed to apply to only one of the subjects at all times for the duration of the treatment.

- Shared / Active: The subject was head tracked, controlled the mouse, and was free to choose where to move within the environment. The partner was not head tracked and did not control the mouse.
- Shared / Driving: The subject was head tracked and controlled the mouse. However, the subject was not free to choose where to move within the environment; the subject’s partner gave instructions on where to move (for example, ‘‘go forward,’’ ‘‘turn right,’’ and so forth). The two subjects could freely discuss where to move, but the partner had final authority.
- Shared / Navigating: The subject was not head tracked and did not control the mouse; the partner was head tracked and did have control of the mouse. However, the subject did have final authority on where to move within the virtual environment, and gave instructions to the other subject accordingly.
- Shared / Passive: The subject was not head tracked, did not control the mouse; the partner was head tracked and did have control of the mouse. Furthermore, the subject had no authority over where to move within the virtual environment, and the partner made all of the decisions about navigation.

The Active and Passive shared treatments were always paired, as were the Driving and Navigating treatments. The Alone conditions and the Shared conditions were each always presented in blocks, and were presented to successive pairs of subjects in alternating order (i.e., the first pair was presented the Alone conditions first; the second pair was presented the Shared conditions first, and so forth). Within each Alone / Shared block, the treatments were counterbalanced via Latin squares. Each trial lasted three minutes.

3.2 Subjects

Subjects were ten men and ten women recruited from university engineering classes or from software companies or associations. Age ranged from 16 to 49, with a mean age of 28 years. Nine subjects had previously experienced virtual reality; five had experienced it for less than ten minutes apiece, while four had experienced it for more than twenty minutes apiece. Sixteen of the subjects (eight pairs) knew each other (e.g., were friends) before taking part in the experiment; the remaining four had not met each other before the experiment. When volunteering for the experiment, subjects either volunteered as pairs (if they knew each other) or were assigned to pairs.

3.3 Presentation of Virtual Environments

The virtual environments were generated using in-house imaging software and a Silicon Graphics Indigo Extreme[2] computer workstation. The images were viewed on a 6 × 8 ft. rear-projection screen using a GE 610 projection system. The stereoscopic images were displayed using a StereoGraphics Corporation time multiplexed shutter technique with a 1280 × 512 pixel resolution. The update rate of the image was six frames per second, a rate reported by Airey, Rohlf, and Brooks (1990) to be just acceptable for a navigation task; this update rate is also approximately equivalent to the lower end of the range of update rates (7–16 Hz) presented by Slater, Usoh, and Steed (1994) in a study on presence in immersive virtual environments.

Subjects were seated in front of the projection screen such that their position subtended a 90 deg. FOV with the display screen. Head tracking was provided by a Polhemus 3Space Fastrak magnetic tracking device. The head-tracking device had three degrees of freedom (translations in X, Y, and Z). Rotation was not incorporated into the device given that the display was nonimmersive and in a fixed location. Subjects navigated through the environment using a mouse located on a small table in front of them. The mouse had two degrees of freedom (forward / backward movement and left / right rotation).

3.4 Presence Questionnaires and Performance Evaluations

One dependent variable represented responses to questions evaluating the sense of presence within the virtual environment and the spatial realism of the virtual environment. The questions were based on questionnaires developed by Barfield and other researchers (Barfield & Hendrix, 1995; Hendrix & Barfield, 1995). The questions on presence represented the subjects' subjective evaluations of their sense of presence both compared to their sense of presence in the real world and within the VE with no comparison to the real world. The questions on the spatial realism of the VE assessed the subjects' subjective evaluations of its realism and the objects in it, as well as the spatial transformations of the VE in response to the subjects' head motions. Subjects also subjectively rated task difficulty and their preferences for copresence and control. Subjects completed a questionnaire at the end of each condition, plus an additional posttest questionnaire. Table 1 presents the questions that appeared in each condition. The first six questions appeared in all conditions.

In addition to the questionnaires, the subjects' performance on the task was also objectively evaluated. This was accomplished by comparing the number of items that the subjects indicated were moved in the virtual room with the actual number of items that were moved. For each condition, the analysis was conducted by examining the subjects' diagrams to determine which objects the subjects identified as having been moved, and the locations the subjects indicated the objects had been moved to. These objects and movements were compared to the actual objects and movements in the version of the room for that condition. The number of times each subject correctly identified both an object and its movement was recorded. These numbers were then converted to percent-correct scores.

4 Results and Discussion

4.1 Presence and Head Tracking

Table 2 presents the mean response and standard deviation for the questions that appeared after each trial,

Table 1. *Presence Questionnaire Items*

Treatment	Questions	Measurement scale
All	1. If your level of presence in the real world is ''100,'' and your level of presence is ''1'' if you have no presence, rate your level of presence in this virtual world.	1–100
	2. How strong was your sense of presence, ''being there,'' in the virtual environment?	1–5
	3. How realistically did the virtual world move in response to your head motions?	1–5
	4. To what degree did the room and the objects in the room appear to have realistic depth / volume?	1–5
	5. Did you feel that you could have reached into the virtual world?	1–5
	6. How difficult was the task?	1–5
Alone / Passive	7. Would your sense of presence have been higher if you had been allowed to navigate within the virtual environment?	1–5
All Shared treatments	8. Did being with a partner affect your sense of presence?	−5–5
Shared / Active Shared / Driving	9. Was your sense of presence affected by the fact that you, not your partner, controlled the mouse?	−5–5
Shared / Navigating Shared / Passive	10. Was your sense of presence affected by the fact that your partner, not you, controlled the mouse?	−5–5
Shared / Active Shared / Navigating	11. Was your sense of presence affected by the fact that you, not your partner, chose where to move within the virtual environment?	−5–5
Shared / Driving Shared / Passive	12. Was your sense of presence affected by the fact that your partner, not you, chose where to move within the virtual environment?	−5–5
All (posttest)	P1. Was your presence more or less when you had a partner with you?	−5–5
	P2. Was your presence more or less when you controlled the mouse?	
	P3. Was your presence more or less when you chose where to move within the virtual environment?	= –

For 1–5 response scales (except for question 6), 1 = extremely so, and 5 = not at all; for question 6, 1 = very difficult, and 5 = very easy.
For −5–5 response scales, −5 = greatly reduced presence, and 5 = greatly increased presence; 0 = no effect.

as well as the result of the Kruskal-Wallis procedure applied to each question. As indicated by the replies to questions 1 and 2 and 4 through 12, there were no statistically significant differences in the subjects' sense of presence among any of the treatments. The means of the reported sense of presence on the 100-point and 5-point scales in the current study were respectively 50.7 and 3.1, with standard deviations of 20.86 and 0.69. These reported levels of presence are rather low, but nonetheless are higher than those reported by Barfield and Hendrix (1995) for a comparable display update rate (41.2 and 3.7 at a 5 Hz update rate; on the 5-point scale, lower numbers indicate higher presence). The levels of presence in the current study are comparable to those reported by Barfield and Hendrix (1995) for a 10 Hz update rate (51.2 and 3.1).

Questions 3 through 5 related to various aspects of the subjects' perception of the virtual environment. A

Table 2. *Means and Standard Deviations (in Parentheses) for the Responses to the Questions as a Function of Treatment*

Question Number	Significance Level	Treatment: Alone Active	Alone Passive	Shared Active	Shared Passive	Shared Driving	Shared Navig
1 Presence (1–100)	$\chi^2 = 1.07, p > 0.05$	52.35 (19.98)	47.90 (22.57)	49.80 (20.43)	49.75 (23.48)	51.50 (21.16)	52.95 (19.56)
2 Presence (1–5)	$\chi^2 = 3.81, p > 0.05$	2.95 (0.51)	3.20 (0.70)	3.00 (0.79)	3.25 (0.79)	3.15 (0.67)	3.05 (0.69)
3 Head movement realism (1–5)	$\chi^2 = 61.26$, $p < .0001$	2.90 (0.64)	4.53 (0.70)	2.80 (0.52)	4.50 (0.86)	2.75 (0.79)	4.28 (1.02)
4 Depth / volume realism (1–5)	$\chi^2 = 6.58, p > 0.05$	2.80 (0.77)	3.05 (0.69)	2.80 (0.62)	3.15 (0.67)	2.95 (0.60)	3.15 (0.67)
5 Reach into world (1–5)	$\chi^2 = 1.08, p > 0.05$	3.25 (0.79)	3.40 (0.82)	3.25 (0.85)	3.40 (0.99)	3.35 (0.88)	3.35 (0.75)
6 Task difficulty (1–5)	$\chi^2 = 3.03, p > 0.05$	3.65 (0.81)	3.30 (0.73)	3.60 (0.82)	3.60 (0.99)	3.35 (0.99)	3.50 (0.83)
7 Presence higher if could navigate (1–5)	n / a	—	2.60 (1.31)	—	—	—	—
8 Partner affect presence (−5–5)	$\chi^2 = 1.56, p > 0.05$	—	—	0.80 (1.15)	1.15 (1.57)	1.25 (1.80)	1.35 (1.57)
9 Presence affected by self control of mouse (−5–5)	$\chi^2 = 1.43, p > 0.05$	—	—	1.85 (1.76)	—	1.15 (1.60)	—
10 Presence affected by partner control of mouse (−5–5)	$\chi^2 = 0.24, p > 0.05$	—	—	—	−0.10 (1.92)	—	0.10 (1.83)
11 Presence affected by self choice of movement (−5–5)	$\chi^2 = 1.73, p > 0.05$	—	—	1.45 (1.73)	—	—	0.63 (1.21)
12 Presence affected by partner choice of movement (−5–5)	$\chi^2 = 0.30, p > 0.05$	—	—	—	−0.16 (2.24)	0.47 (2.22)	—

For 1–5 response scales (except for question 6), 1 = extremely so, and 5 = not at all; for question 6, 1 = very difficult, and 5 = very easy.

For −5–5 response scales, −5 = greatly reduced presence, and 5 = greatly increased presence; 0 = no effect.

For questions 1–6, df = 5; for question 8, df = 3; for questions 9–12, df = 1.

Kruskal-Wallis analysis of the questionnaire responses revealed that the subjects experienced no significant changes in the sense of presence as a function of head tracking. The only significant effect was for question 3, the realism of the movement of the virtual world in response to the subjects head motions ($\chi^2 = 60.66$, $p < 0.0001$). Unsurprisingly, head-tracked subjects reported this realism to be significantly higher than subjects who were not head tracked (Mean (HT) = 2.82, SD = 0.65; Mean (Passive HT) = 4.53, SD = 0.70; Mean (No HT) = 4.39, SD = 0.93). There was a trend toward significance for question 4, the apparent depth / volume realism of the virtual environment ($\chi^2 = 5.66$, $p < 0.06$), with subjects who were head tracked reporting greater realism (Mean (HT) = 2.85, SD = 0.66; Mean (Passive HT) = 3.15, SD = 0.66; Mean (No HT) = 3.05, SD = 0.69).

Although Hendrix and Barfield (1995) did not investigate the effect of head tracking on the depth / volume realism of the virtual world or on the feeling of being able to reach into the virtual world, they did find that stereopsis improved both the depth / volume realism and the feeling of being able to reach into the virtual world. The results of the current study suggest that head tracking also improves the depth / volume realism of the virtual environment. The current study found no significant effect of head tracking on the feeling of being able to reach into the virtual world (question 5), suggesting that this feeling may be a function of stereopsis only.

There are two potential concerns with the interpretation of these findings. The first is that there were large individual differences between subjects in their use of head tracking. Most of the subjects did not attempt to use the head tracking to improve their performance on the task; for example, rather than moving their heads to look around or over an object, they would navigate using the input device to a position where they could see beyond the object. A smaller number of subjects did use head tracking to look around objects; for example, if there were something on the room's kitchen table that was obscured by the back of a chair set at the table, they would lean forward to look over the back of the chair. Therefore, even if head tracking were implemented in a nonimmersive (large-screen or desktop display) VE system, there is no guarantee that it would be fully exploited by the participants. The second concern is that hardware capabilities and the visual complexity of the VE in this study restricted the update rate of the system to 6 Hz. Although this update rate is acceptable for navigation tasks (Airey et al., 1990), it is likely that the sense of presence as reported by the subjects would have been higher, and the effects of head tracking with an improved response rate more significant.

Given these two caveats, these results suggest that head tracking may be used with some success in copresent VEs used for educational and learning tasks. Because there is only one display in copresent systems, there is only one viewpoint into the virtual environment. If an educational application were to require simultaneous exploratory behavior by multiple students, this limitation to one viewpoint would limit the usefulness of a copresent system for that application. Similarly, if head tracking were required for students to perform the task, the usefulness of copresent systems would be limited, as the single display means that only one student at a time could control the viewpoint via head tracking. Conversely, if it were desirable to have one controlled viewpoint, as it might be in some training applications, then copresent systems with single-user head tracking may be quite suitable. However, if an application required spatial relationships and transformations to be experienced as realistically as possible by each student, the beneficial effect of head tracking on depth / volume realism suggests that it would be valuable to have each student individually head tracked, requiring a separate display for each student. We also believe that it would be valuable to continue research on copresence in complex virtual environments using VEs with improved update rates, to better determine the effects of head tracking in copresent systems.

4.2 Task Performance

The results focusing on the number of items found were analyzed using an ANOVA procedure (General Linear Model). When comparing working alone versus working with a partner, there was a significant difference ($F(1, 118) = 6.55$, $p < 0.05$), with copresence yielding more objects found (mean (copresent) = 75% found, mean (alone) = 65% found). When comparing the Alone / Active treatment versus the Alone / Passive treatment versus the Shared treatments, the ANOVA indicated a significant difference in the number of objects found ($F(2, 117) = 4.51$, $p < 0.05$). The Duncan multiple-comparison test indicated that the Alone / Passive condition resulted in significantly fewer items found compared to the Alone / Active and the shared conditions, with no significant difference between the latter two (mean (Alone / Passive) = 60% found, mean (Alone / Active) = 70% found, mean (Shared) = 75% found).

When comparing head tracking versus no head tracking, the ANOVA indicated no significant difference between the number of items identified ($F(1, 118) = 0.86$, $p > 0.05$). However, when comparing head tracking (in the Active treatments) versus no head tracking (in the Alone / Passive treatment) versus passive head tracking (in the Shared treatments, when the subject was not head tracked but the partner was), the ANOVA indicated a significant difference in the number of objects found ($F(2, 117) = 4.02$, $p < 0.05$). The Duncan multiple-comparison test indicated that the no-head-tracking condition resulted in significantly fewer items found compared to head tracking and passive head tracking, with no significant difference between the latter two (mean (No tracking) = 60% found, mean (Tracking) = 73% found, mean (Passive tracking) = 75% found).

When comparing the six treatments to assess the effects of differing levels of control, the ANOVA indicated a slight trend toward a difference in the number of items found ($F(5, 114) = 1.98$, $p < 0.10$). The Duncan multiple-comparison test indicated that the Alone / Passive treatment resulted in significantly poorer task performance than any of the other treatments, and that there were no significant differences among the other treatments (mean (Alone / Passive) = 60% found, mean (Other) = 73.75% found). It is this difference between the Alone / Passive treatment and the other treatments that causes the significant differences to appear in the ANOVA procedures reported above.

One potential explanation for the similar task performance in all but the Alone / Passive treatment is that the experimental task may not have been sufficiently difficult to assess subtle effects of copresence, head tracking, and control on task performance. If one participant could perform the task as well as two could, then there should be no effects for copresence. Another potential explanation is that the Alone / Passive condition presented the subjects with the lowest possible level of control over interactions with the environment. Because they could not interact with the environment, they had little or no choice of strategies for performing the task. In contrast, all of the other treatments enabled the subject or pair of subjects to choose how they would go about performing the task.

4.3 Copresence

A Kruskal-Wallis analysis of questions 1 through 6, which appeared in all treatments, indicated that the copresence of participants did not affect the subjects' sense of presence, perceptions of the virtual environment, or opinion of task difficulty. The finding that copresence did not affect the subjects' sense of presence—although counter to our expectations—in hindsight may be explainable by considering the sense of presence in the real world. In the real world, the presence or absence of another person does not affect our sense of presence in the environment. The results of the current study indicate that this was also the case when two participants shared the same virtual environment. Furthermore, it may also be that the sense of presence is only one of a number of similar factors that affect the nature of experiences in virtual environments, and that the questionnaires presented to the subjects were unable to assess these other factors. For example, previous research (Barfield & Hendrix, 1995; Hendrix & Barfield, 1995; Hirose et al., 1994; Slater et al., 1994) has indicated that the sense of presence in virtual environments is affected by the methods by which virtual images are displayed. If these display factors are the primary determinants of presence, then the copresence of other participants should have little or no effect on the sense of presence.

On the other hand, there may be elements to participants' experience in virtual environments that are unrelated to the sense of presence per se. If these elements are influenced by copresence, the quality of the participants' experience may be affected even though their sense of presence is unchanged. The subjects' answers to the posttest question ''Was your presence more or less when you had a partner with you?'' suggest that this may be the case: subjects who knew each other before participating in the experiment reported that they had significantly higher presence than did subjects who did not know each other before the experiment (mean: 1.13, SD: 1.42 versus mean: −0.50, SD: 1.14; $\chi^2 = 20.96$, $p < 0.0001$), even though their levels of presence after each treatment were not significantly different from those of subjects who did not know each other. This result suggests that interpersonal interaction is indeed a factor in the quality of experience in virtual environments; the subjects who knew each other before the experiment may have been able to engage in richer interpersonal discourse due to their greater familiarity with each other, and thus had a more satisfying experience, which they expressed as a higher level of presence on the posttest question. This finding is supported by Hirose et al. (1994), who report that a visually and auditorially immersive environment with no interpersonal interaction provided a high level of presence, whereas an environment that was only visually immersive but that had interpersonal interaction provided a lower degree of presence but was nonetheless satisfying because of the interaction.

This interpersonal interaction may also have a slight effect on the sense of presence itself, as suggested by a trend toward higher presence on question 2, rating the sense of presence on a scale of 1 to 5, among those subjects who knew each other ($\chi^2 = 3.14$, $p < 0.08$); subjects who knew each other before the experiment reported their sense of presence (mean: 3.05, SD: 0.70) to be higher than subjects who did not know each other (mean: 3.29, SD: 0.62). Similarly, participants who are familiar with each other may be able to give up some degree of control over the interaction with the environment without suffering significant losses in presence, as suggested by the trend toward significance on question 10, rating the effect on the sense of presence of the fact that the partner, not the subject, controlled the mouse ($\chi^2 = 3.14$, $p < 0.09$). Subjects who knew each other before the experiment reported their sense of presence to be slightly increased (mean: 0.25, SD: 1.92), whereas subjects who did not know each other reported their sense of presence to be decreased (mean: −1.00, SD: 1.20). Participants' familiarity with each other may enable them to predict or easily adapt to their partners' actions, and thus yield higher levels of presence than among participants who are not familiar with each other.

These results suggest that copresent virtual environments may prove to be a valuable tool for some applications involving multiple members. Because the copresence of two participants does not affect each participant's sense of presence given a backlit projection system, designers of virtual worlds can concentrate on selecting appropriate display methods to enhance presence without needing to be concerned with confounding effects by the copresent participants. Furthermore, although copresence does not increase the participants' sense of presence, neither does it decrease the sense of presence, so users of VE systems need not be concerned with degradations in performance that are caused by reductions in the participants' sense of presence due to copresence. Conversely, it appears that, even though copresence does not affect the sense of presence itself, it nonetheless improves the quality of the participants' experience, provided that the participants are familiar with each other. The richness of the face-to-face communication afforded by copresent systems appears to yield a more rewarding experience, as earlier suggested by Yoshida and Kakuta (1994), which may in turn lead to improved user satisfaction and potentially greater performance. The finding that copresence did not affect subjects' estimates of task difficulty in this study may be due to the nature of the task in the study. Depending on the nature of tasks in other virtual environments, copresence may or may not affect the difficulty of task performance.

4.4 Constructs in the Experience of the Virtual Environment

A factor analysis was performed on the first six questions of the questionnaires to examine the interrelationships among the questions. (The factor analysis was limited to the questions that appeared on every posttreatment questionnaire.) Factor analysis is an interdependence statistical technique that provides a means to determine what underlying factor or factors may identify groups of related questions. It considers all questions simultaneously; the factors are extracted by rotating the variables and observing which variables load high on a particular factor. In the current study, the variables were rotated orthogonally with a VARIMAX rotation. The factor loadings represent the correlation between the original questions and the derived factors. Table 3 presents the factor labels and the percentage of total variance accounted for by each of the three factors. As indicated in the table, three underlying factors were found and labeled as follows: (1) presence in the virtual environment, (2) quality of the virtual environment, and (3) task difficulty.

We propose that the first factor, presence in the virtual environment, relates to the degree to which the subjects became psychologically engaged in the VE; this factor comprises questions 1, 4, and 5. For participants in the virtual environment to feel a sense of presence in the virtual environment, they must suspend their disbelief that the VE is not merely a computer-generated image, and choose to perceive the imagery as an environment or actual place visited. It is this engagement in the virtual environment that enables the participant to become psychologically immersed. The questions in this factor address the degree to which the participants become engaged in the virtual environment as compared to the real world. Questions 4 and 5 address the realness of the image as environment: question 4 relates to how realistically the virtual environment appears, while question 5 relates to the subject's impression of being able to reach into the environment. We posit that subjects cannot perceive an image as an environment unless the environment would somehow appear realistic to them; similarly, if the participants choose to believe that the projected image is an environment, they should feel as if they could reach into it. Question 1 relates to the subjects' sense of presence in the virtual environment as compared to their sense of presence in the real world. We believe that this continuum presented to the subjects encourages them to compare the virtual environment with the real-world environment, and thus to evaluate the image they perceive as an environment.

Table 3. *Factor Structure of Questions and Question Loading for Each Factor*

Items	Loading
I. Presence in the virtual environment *Contribution to total variance: 41.7%*	
(1) If your level of presence in the real world is ''100,'' and your level of presence is ''1'' if you have no presence, rate your level of presence in this virtual world.	−0.75137
(4) To what degree did the room and the objects in the room appear to have realistic depth / volume?	0.83109
(5) Did you feel that you could have reached into the virtual world?	0.83934
II. Quality of the virtual environment *Contribution to total variance: 17.8%*	
(2) How strong was your sense of presence, ''being there,'' in the virtual environment?	0.64957
(3) How realistically did the virtual world move in response to your head motions?	0.88336
III. Task difficulty *Contribution to total variance: 17.3%*	
(6) How difficult was the task?	0.89806

We propose that the second factor, ''quality of the virtual environment,'' relates to the degree of the participant's presence in the virtual environment and to the realism of the spatial transformations perceived by the participant within the virtual environment; this factor comprises questions 2 and 3. The questions in this factor address the quality of experience solely within the context of the virtual environment, without comparing the virtual environment to the real world. Question 2 relates to the subject's sense of presence inthe virtual environment. We had originally expected questions 1 and 2 to fall within the same factor, as they did in Barfield and Hendrix (1995); however, this was not the case in the current experiment. Note, however, that the current study presented different virtual environments, conditions, and tasks than did Barfield and Hendrix (1995), so it should not necessarily be expected that the two questions would fall into the same factor in both studies. The two questions differ in the way that they ask the subjects to assess their sense of presence in the virtual environment. Question 1 asks the participants to compare their sense of presence in the virtual environment to their sense of presence in the real world, while question 2 asks the participants only about their sense of presence in the virtual environment. Question 2 thus asks participants to judge their sense of presence solely within the context of the virtual environment, and we therefore posit that this judgment is not dependent on the gross perception of the computer-generated imagery as an environment as compared to the real world. Question 3 relates to the transformations of the virtual environment as the subjects move their heads; the more realistic the spatial transformations, the higher the spatial realism of the virtual environment. The third factor, ''task difficulty,'' relates, not surprisingly, to the difficulty of performing the task; this factor comprises question 6.

5 Conclusions

The present study suggests that copresent multiuser virtual reality systems may be valuable for a variety of educational or training applications, as they provide a way for multiple users to simultaneously interact both interpersonally and with a dataset. More specifically, these systems allow a number of users to simultaneously see the same projected image, while providing for centralized control with the data set and affording face-to-face communication among the participants. The participant's sense of presence is neither helped nor hindered by the copresence of multiple participants, although the copresence and communication may enrich the experience in other ways. The unified viewpoint and single-user control does not reduce the participant's sense of presence, although users do prefer to have individual control over their interactions. Because copresent virtual reality systems are likely to be technologically simpler to design and implement than distributed systems, they may prove to be of particular value for certain applications.

We believe that the psychological and social aspects of multiuser virtual environments, both distributed and copresent, should continue to be addressed by researchers. First, the current study suggests that the sense of presence is not the only subjective factor that helps determine the overall quality of experiences in virtual environments. These other factors—such as the social interaction between participants, the participants preferences for control and interaction with the virtual environment, and the effects of familiarity and realism of the virtual environment—should be examined, particularly as they may contribute to overall user satisfaction with virtual reality systems. Second, we believe that there should be more-detailed examination of the relative roles of display factors, control factors, and social factors in the use of virtual environments, as we believe that it would be necessary to weigh these different factors carefully in designing virtual reality systems for specific purposes. We hope that the current study provides a useful starting point for research into this complex issue.

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